ECOLE MOHAMMADIA D'INGÉNIEURS

Optimization techniques in civil engineering

Development of Future Rule Curves for Multipurpose Reservoir Operation

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I. Problematic and choice justification

Due to climate change and land-use change caused by population and economic growth, water resource issues have become more complex. In consequence, Improving the reservoir operation for increased efficiency is a necessary way of supply management site, which does not require the physical development of reservoir. Normally, reservoir operation uses upper and lower rule curves to consider the release of water from the reservoir responding to downstream demands in long-term operation. Optimal rule curves are necessary guidelines in the reservoir operation that have been used to assess performance of any reservoir to satisfy water supply, irrigation, industrial, hydropower, and environmental conservation requirements. The reservoir management agency needs to plan in advance the appropriate volume of water in the reservoir (at each time interval) for storage and release of water for various purposes, including the implementation of the plan as long as the relevant factors in the future have not changed from the original. However, if future conditions are different from those anticipated in the planning phase, performance may differ from planned to minimize water shortage or overflow. The rule curve assumptions are based on maintaining the water level (or volume of water) in the reservoir to appropriate the changing hydrological situation and downstream water allocation. The main purpose is to avoid the risk of water shortages and floods in the reservoir and downstream areas. During the dry season, reservoirs need to maintain water volume to reduce the risk of water levels lower than minimum storage. During the rainy season, the reservoir must release water to reduce the storage volume, which can support the precipitation and inflow that flows into the reservoir. The reservoir rule curves have been improved to provide the optimal solution for long-term operation.

This study proposed a conditional tabu search algorithm (CTSA) to connect with the simulation model for searching the optimal reservoir rule curves. A minimum average water shortage was used as the objective function for the searching procedure. The proposed model has been applied to determine the optimal rule curves of the Ubolrat Reservoir in the northeast region of Thailand with the historic monthly inflow, future inflow under scenario B2, water demand, hydrologic data, and physical reservoir data. Comparison of the conditional genetic algorithm (CGA) and the CTSA was shown to demonstrate the effectiveness of the proposed CTSA model.

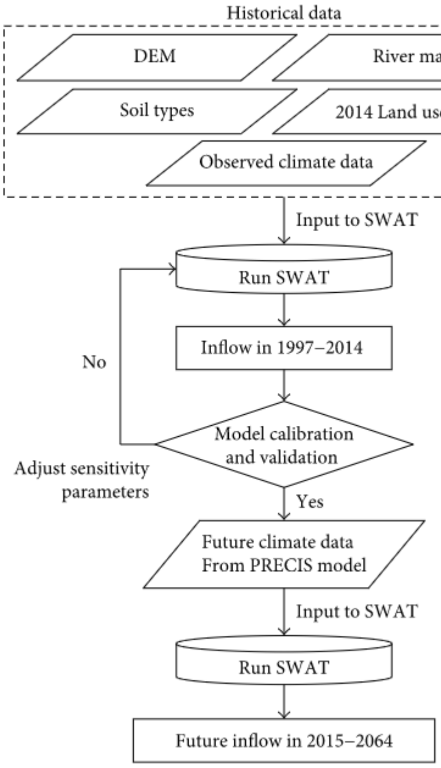
II. Methodology

1. The Future Inflow

The development of the optimal future rule curves will use data from the future inflow using the PRECIS model (Providing REgional Climates for Impacts Studies) considering the effects of climate change. the future inflow will be produced using the SWAT hydrological model. PRECIS is a regional climate model, based on the development of ECHAM4 model, displaying the data as “grid” with high solution of 22 × 22 km². The data recorded during 1997–2014 were used as a baseline to predict those for 2015 to 2064.

SWAT (Soil and Water Assessment Tool) is a semidistributed hydrological model developed for the measurement of the inflow, sediment, and water quality under the climate and land-use changes. SWAT can be used to continually measure the daily inflow and define a longer period of time in the future. It can also connect and import the spatial data from the Geographic Information System (GIS) in order to evaluate the inflow.

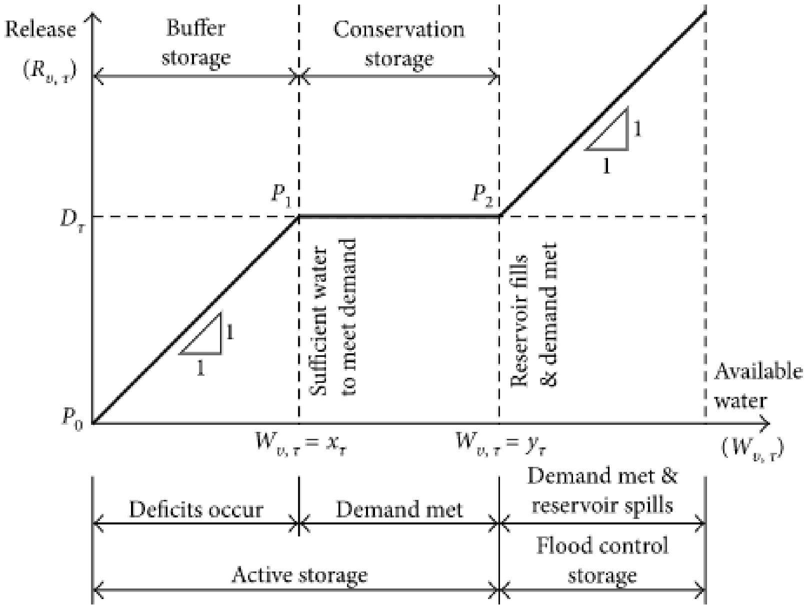
The accuracy of the SWAT results can be evaluated by comparing the simulated data with that recorded data from the observation station. Three variables including R2 (coefficient of determination), RE (relative error), and Ens (Nash-Sutcliffe simulation efficiency) were considered as the key indicator of the accuracy. In general, SWAT needs to modify the value of hydrological parameters for the model calibration and validation. In this study, 8 parameter values were used including Alpha_BF, Gwqmn, Gw_Revap, Sol_Awc, Epco, Esco, Ch_N2, and Gw_delay. Then, the SWAT with adjusted sensitivity parameters was optimized. Later, the daily future climate data from PRECIS that had been downscaled were classified into 50 years in future periods; the processes of model setup are shown in Figure 1.



2. Reservoir Operation Model

Figure 2

Standard operating rule.



The reservoir operation is performed using water usage criteria release, operating policies, and reservoir rule curves with monthly data for long-term period. A reservoir operation model was constructed on the concept of water balance, and it can be used to simulate reservoir operation effectively.

At the point P1, the available water is equal to the water demand, and at the point P2, the available water is the total of reservoir capacity and water demand. If the available storage is between P1 and P2, water release is equal to water demand. If the available water exceeds the sum of active storage and water demand, the reservoir will release the excess spilled. And:

$$R_{\nu,\tau} = \begin{cases} D_\tau + W_{\nu,\tau} - y_\tau & \text{for } W_{\nu,\tau} \geq y_\tau + D_\tau \\ D_\tau & \text{for } x_\tau \leq W_{\nu,\tau} < y_\tau + D_\tau \\ D_\tau + W_{\nu,\tau} - x_\tau & \text{for } x_\tau - D_\tau \leq W_{\nu,\tau} < x_\tau \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

$$W_{\nu,\tau} = S_{y,\tau} + Q_{\nu,\tau} - R_{\nu,\tau} - E_\tau - DS, \tag{2}$$

where $R_{v,\tau}$ is the released water from the reservoir during year v and period τ (τ = 1 to 12, representing January to December), D_τ is the water demand of month τ; x_τ is the lower rule curve of month τ; y_τ is the upper rule curve of month τ, and $W_{v,\tau}$ is the available water calculating by a simple water balance, as described in (2). $S_{v,\tau}$ is the stored water at the end of month τ; $Q_{v,\tau}$ is the monthly inflow to reservoir, E_τ is the average value of evaporation loss, and DS is the minimum reservoir storage capacity (the capacity of dead storage).

In (2) and Figure 2, if available water is in the range of the upper and lower rule levels, then demands are satisfied in full. If available water is over the top of the upper rule level, then the water is spilled from the reservoir in downstream river in order to maintain water level at the upper rule level. If available water is under the bottom of the lower rules level, a reduction of water release is performed.

3. Application of CGA with the Reservoir Simulation Model for Searching Rule Curves:

The CGA and reservoir simulation model for searching the rule curves are described in Figure 3

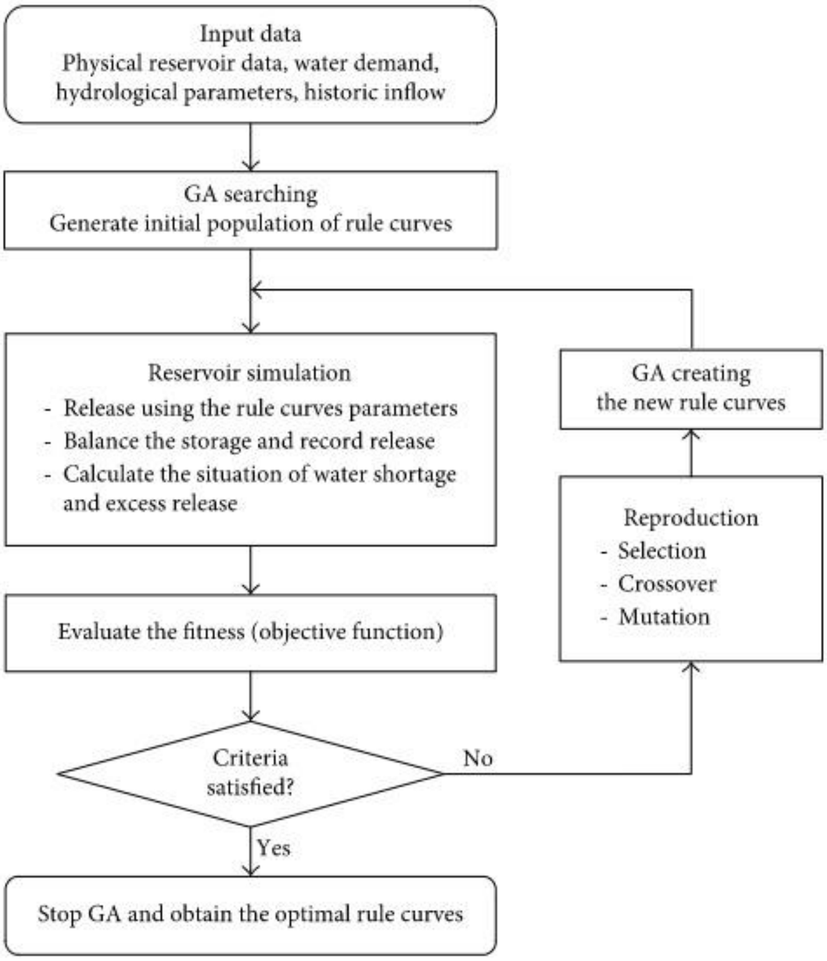

Input data
Physical reservoir data, water demand, hydrological parameters, historic inflow
GA searching
Generate initial population of rule curves
Reservoir simulation
- Release using the rule curves parameters
- Balance the storage and record release
- Calculate the situation of water shortage and excess release
Evaluate the fitness (objective function)
Criteria satisfied?
No
Yes
Stop GA and obtain the optimal rule curves
GA creating the new rule curves
Reproduction
- Selection
- Crossover
- Mutation

Figure 3

Applying CGA and reservoir simulation for searching rule curves.

The CGA requires an encoding format to change the decision variables into the form of chromosomes. The CGA, which consists of selection, crossover, and mutation, is executed. After this stage, the genetic operations will create new chromosomes. For this study, each decision variable represents the average monthly water storage of the rule curves in the reservoirs, which are defined as the upper bound and the lower bound. After the first set of chromosomes in the initial population have been calculated (24 decision variables, which consist of 12 values from the upper bound and 12 values from lower bound situations), the released water will be recalculated by the reservoir simulation model using these rule curves. Next, the released water is used to determine the objective function with the aim of assessing the fitness of the GA. After that, the reproduction process will create new rule curve values in the next generation. This procedure is repeated until the 24 values of rule curves are appropriate.

the objective function for searching the optimal reservoir rule curves is the minimum of the average water shortage ($\min_{(avr)}$) in million cubic meters (MCM) per year, as shown in

$$\min_{(\mathrm{avr})} = \frac{1}{n}\sum_{v=1}^{n} Sh_{v}, \tag{3}$$

where n is the total number of considered years and Sh_v is the water deficit during year v (a year that does not meet 100% of the target demand).

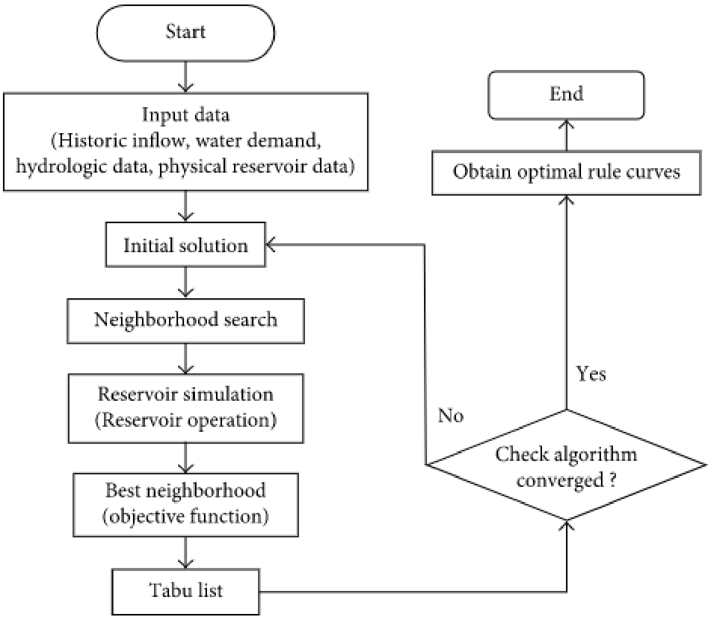
4. Applying Conditional Tabu Search Algorithm for Searching Rule Curves

The CTSA begins with an initial population $\{X_1, X_2, \ldots, X_n\}$ created randomly within the feasible space. With the 24 decision variables (rule curve variables for both upper and lower), the feasible solution of the iteration ith is represented as $X_i = [x_{i1}, x_{i2}, \ldots, x_{i24}]^T$. Then, a set of rule curves is used in reservoir simulation, and the released water is calculated by the simulation model using these rule curves. Next, the released water is used to calculate the fitness function to evaluate the feasible solution. The fitness function is the minimum of the average water shortage (Z) subject to constraints on the simulation model as described in (3).

Then, the process is continued until the termination criterion is satisfied as described in Figure 4. This termination criterion is optimum; it can be expressed by a slight change in the fitness values (less than 0.10 MCM).

Figure 4

Applying tabu and reservoir simulation for searching rule curves.



5. Illustrative Application

The Ubolrat Basin is a branch of the Chi Basin located in northeastern Thailand (Figure 5). It has an area of about 3,282 km^2. The average annual rainfall is 1,411 mm, and the mean annual temperature is 27°C. The Phong River lies in the middle of the basin. The Ubolrat Dam was developed by building an earth core rock fill dam across the Phong River with a height of 33 m and crest length of 7,800 m. The normal storage capacity and average annual inflow are 2,263 MCM and 2,478.591 MCM, respectively. The objectives of the Ubolrat Dam are irrigation, flood control, and industrial and domestic water supply. Schematic diagram of Ubolrat basin is described in Figure 6.

Figure 5

Location of the Ubolrat Dam.

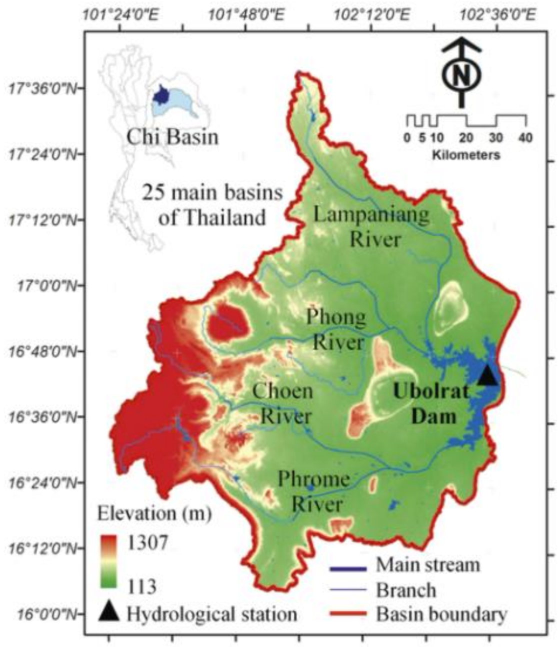
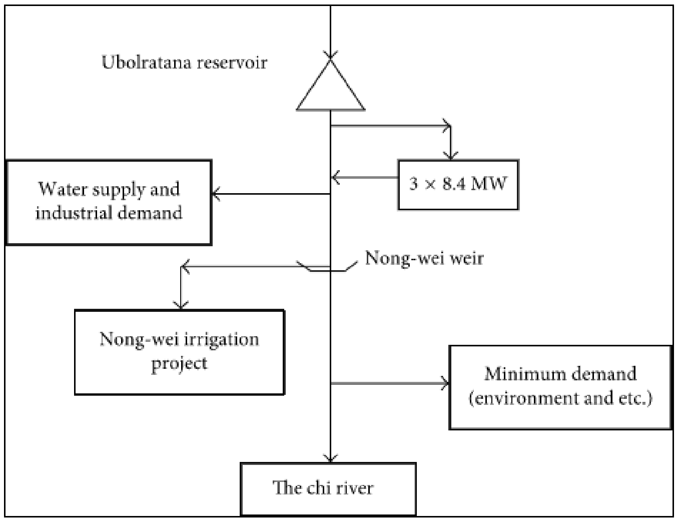


Figure 6

Schematic diagram of the Ubolrat basin.


Ubolratana reservoir
3 × 8.4 MW
Water supply and industrial demand
Nong-wei weir
Nong-wei irrigation project
Minimum demand (environment and etc.)
The chi river

The study used CTSA in connection with a reservoir operation model to find optimal rule curves through the MATLAB toolbox. The optimal rule curve can then be applied to an actual scenario depending on whether the rule curve can be used to cover every case or event that might occur. Thus, the HEC-4 model was used to create the synthetic inflow data into the monthly inflows as a synthetic data set of 500 events. This method was based on the actual historic monthly inflow of the Ubolrat Reservoir between years 1963 and 2014 (50 years) imported to the HEC-4 model to generate the synthetic inflow event. (1 event is a representative period of 50 years.) Therefore, the monthly inflow data are 300,000 values (50 years × 12 months × 500 events). Then, input synthetic inflow data were used to assess the efficiency of the new rule curves and compare them with the existing rule curves and also between the CTSA and CGA model under the same conditions. Further, the new obtained rule curves from CTSA and CGA model were used to evaluate with the future situation of B2 scenario. The future inflows to reservoir were created by SWAT model that considered climate changes.

III. Results and Discussion

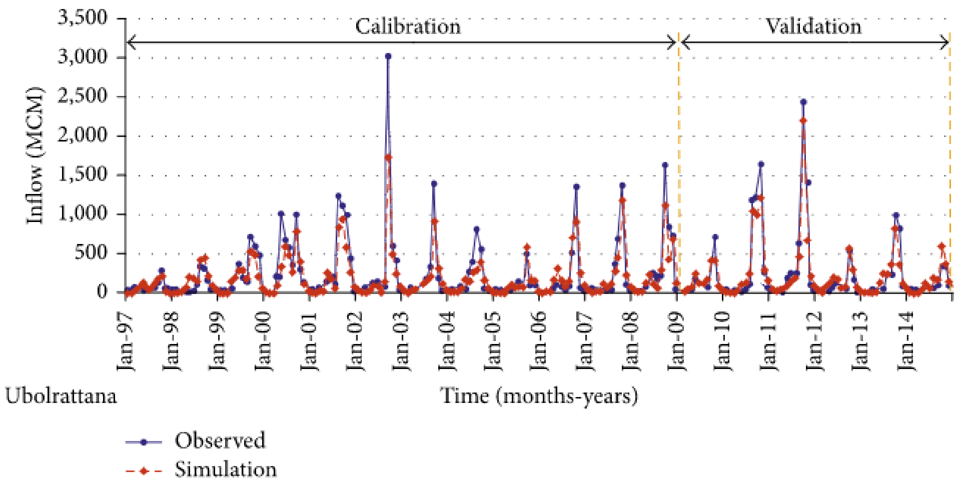
1. Future Inflow into the Ubolrat Reservoir:

An evaluation on SWAT accuracy used the data found during 1997–2014 (18 years; 1997–2008 for calibration and 2009–2014 for validation) for Ubolrat Reservoir station.

The inflow calculated by SWAT and compared with the data from the two observed station shows the inflow during the period of model calibration and validation; meanwhile, R^2, RE, and E_{ns} were satisfactory and accurate as the deviation can be accepted. the goodness of fit of the data was depicted in Figure 7.

Figure 7

The comparison between the runoff from the observed stations and the SWAT result.



The inflow at the Ubolrat Reservoir station simulated by SWAT was divided into 2 phases: (1) baseline inflow which is the climate and spatial data recorded during 1997–2014 and (2) future inflow using the climate data from PRECIS model resulted during 2015–2064. The inflow analysis indicates that an average volume of the baseline inflow was 2,736 MCM and an average volume of the future inflow was 4,580.5 MCM. When comparing those two volumes, it was noted that the future inflow seems to be increased (1,844.5 MCM or 40.3% in 50 future years). Figure 8 illustrates the annual inflow simulated by SWAT during 2015–2064, and Figure 9 depicts the comparative result between the average baseline inflow and the average 10-year future inflow with increased trend in the future period, most of which have shown more than 4,000 MCM, except the third period. This result shows that the future inflow flows into the Ubolrat Reservoir with increased volume.

Figure 8

Annual future inflow flowing into Ubolrat Reservoir during 2015–2064.

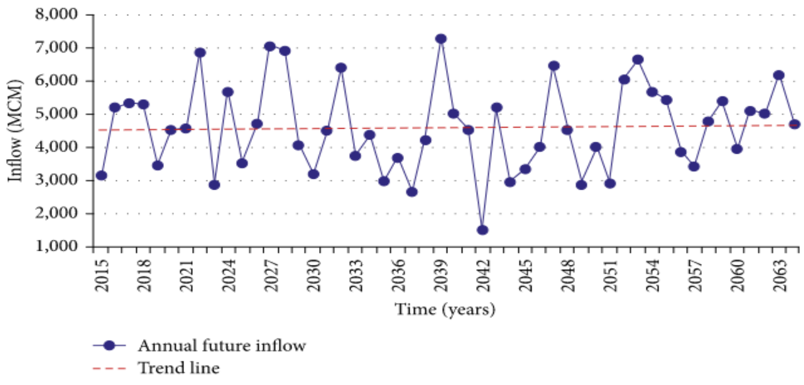
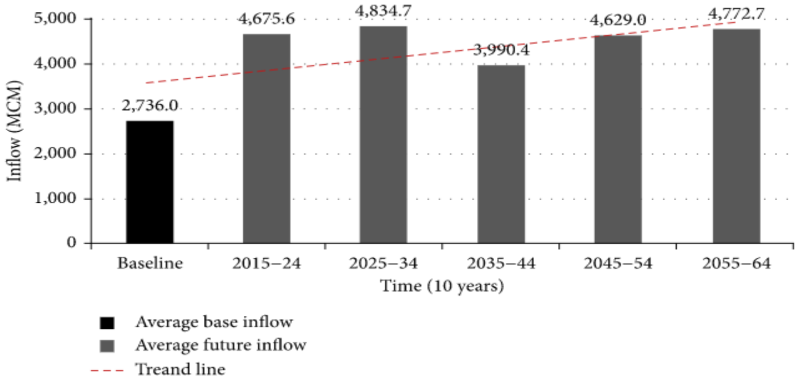


Figure 9

Average 10-year future inflow flowing into Ubolrat Reservoir compared with the baseline.

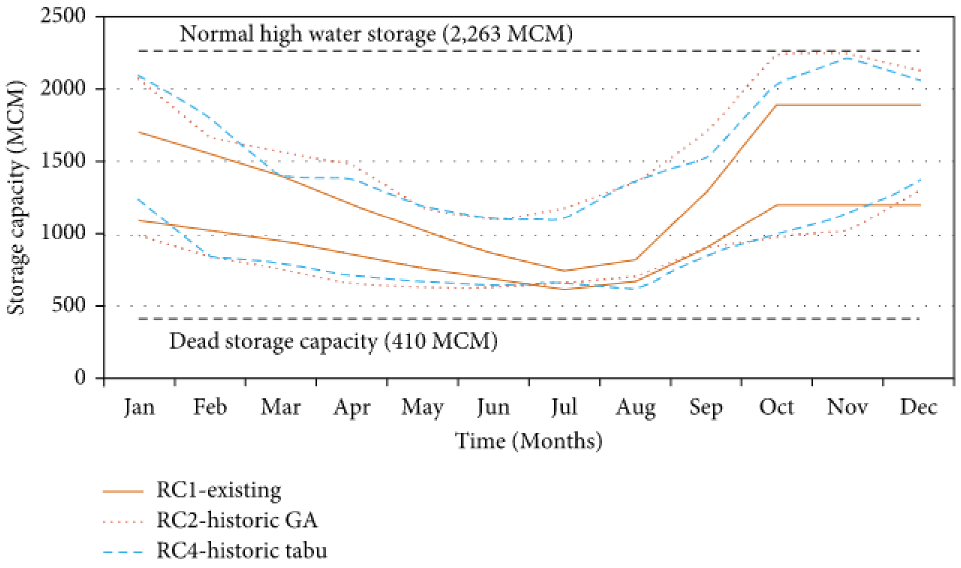


2. Optimal Historic Rule Curves:

The historic data of inflow, evaporation, water requirement, and monthly rainfall were imported for processing in the CGA connected to the simulation model and CTSA model, and the optimal rule curves were obtained.

Figure 10

Optimal historic rule curves of the Ubolrat Reservoir.



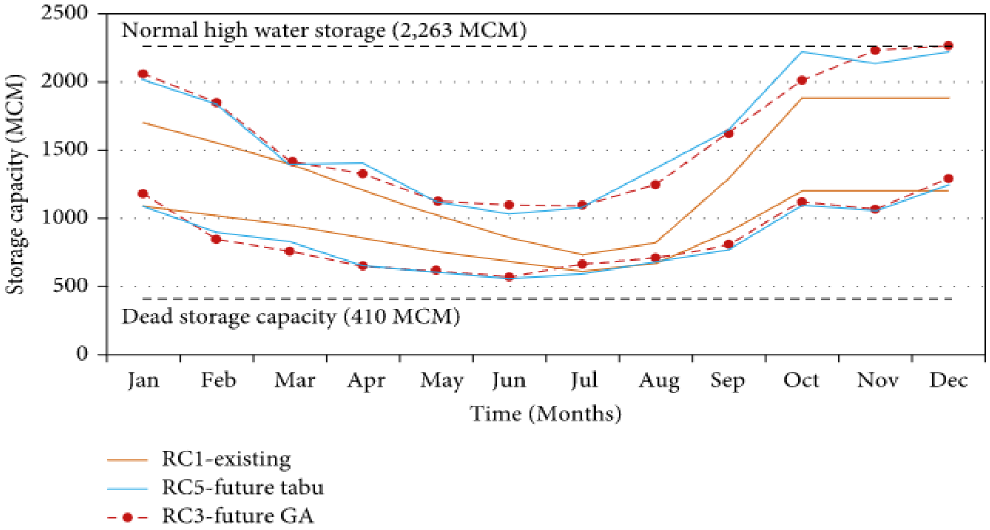
We observe that the water storage levels of the CTSA and CGA lower rule curves are lower than the existing rule curves during the dry season (February–June) in order to release more water to reduce water scarcity. In the middle of rainy season (August–October), the CTSA and CGA upper curves are higher than their existing rule curves in order to increase water storage for next dry season. This will help alleviate water shortages in the next year.

3. Optimal Future Rule Curves :

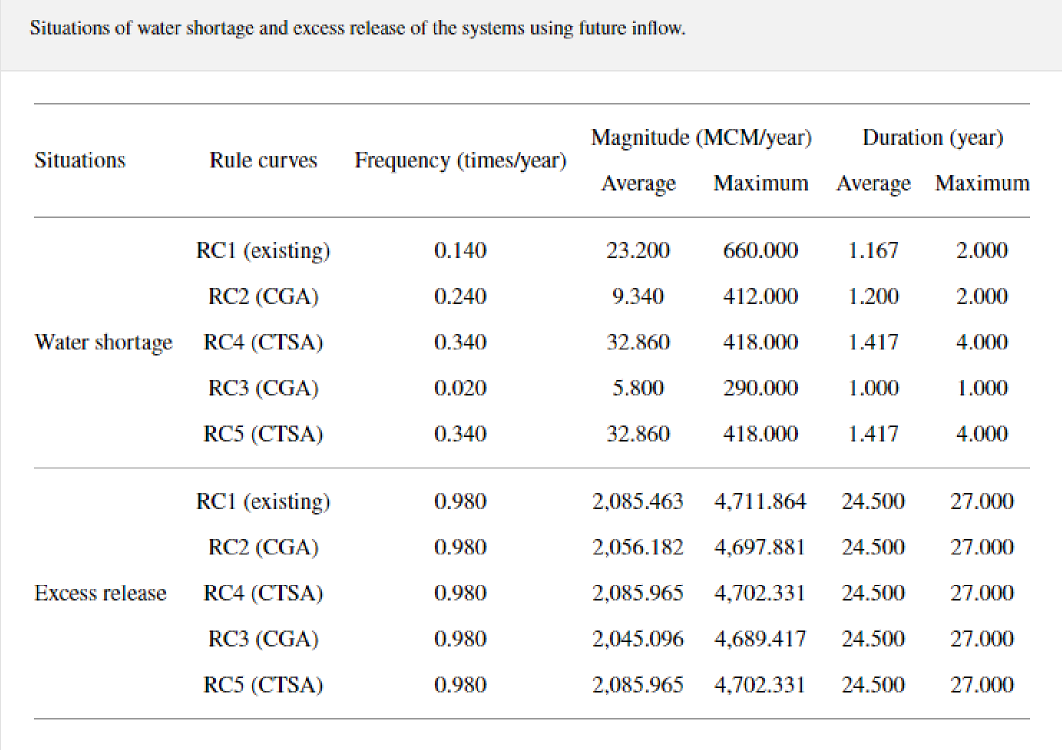
To find the future rule curves, the average monthly inflow for the future period 2015–2064 under the B2 scenario was imported into the CGA and CTSA model, and then, the optimal future rule curves were obtained. Figure 11 shows the optimal upper and lower rule curves of the CGA (RC3) and CTSA (RC5) compared with the existing rule curves (RC1).

Figure 11

Optimal future rule curves of the Ubolrat Reservoir.



4. Performance of Optimal Rule Curves



Situations of water shortage and excess release of the systems using future inflow.

Situations	Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
Water shortage	RC1 (existing)	0.140	23.200	660.000	1.167	2.000
	RC2 (CGA)	0.240	9.340	412.000	1.200	2.000
	RC4 (CTSA)	0.340	32.860	418.000	1.417	4.000
	RC3 (CGA)	0.020	5.800	290.000	1.000	1.000
	RC5 (CTSA)	0.340	32.860	418.000	1.417	4.000
Excess release	RC1 (existing)	0.980	2,085.463	4,711.864	24.500	27.000
	RC2 (CGA)	0.980	2,056.182	4,697.881	24.500	27.000
	RC4 (CTSA)	0.980	2,085.965	4,702.331	24.500	27.000
	RC3 (CGA)	0.980	2,045.096	4,689.417	24.500	27.000
	RC5 (CTSA)	0.980	2,085.965	4,702.331	24.500	27.000

In the case of future situation (Table), the future rule curves (RC3 and RC5) showed the best performance, as indicated by the frequency of the water shortage and the average and the maximum magnitudes of the water shortages. The future rule curves are more suitable for future situations than the existing rule curves and the historic rule curve.

IV. Conclusion:

1. Is it possible to broaden this subject?

To search optimal rule curves of the reservoir is a nonlinear optimization problem. There are many optimization techniques that are applied to connect with the reservoir simulation model for searching optimal rule curves such as dynamic programming (DP), genetic algorithm (GA), and simulated annealing algorithm (SA). Those obtained rule curves are effectively applied for each area. However, these new optimization techniques have not been applied to find the optimal rule curves like the tabu search technique.

2. How about the application in Morocco?

This method is not hard to use because all we need is historical data, spatial data and future expectations from existing studies, to start looking for the optimum future curves. It’s something necessary and very helpful that help to avoid many catastrophes such us floods, as we saw at Casablanca and Tetouan recently.

3. Conclusion

This study proposed an alternative algorithm for searching optimal reservoir rule curves. The conditional tabu search algorithm (CTSA) and reservoir simulation model were applied to search the optimal rule curves of the Ubolrat Reservoir under historic monthly inflow and future inflow under the scenario B2. The future inflow and synthetic inflow data of reservoirs were used to simulate reservoir system for evaluating situations of water shortage and excess release. The results found that the new obtained rule curves from CTSA are more suitable for reservoir operating than the existing rule curves. The frequency and magnitude of water shortage and excess water release for using new obtained rule curves are lower than the existing rule curves. When comparing the new obtained rule curves from CTSA with the rule curves of the CGA method as well as the existing simulation method, it was found that these rule curves are similar.

The proposed CTSA model is an effective method for application to find optimal reservoir rule curves. This reveals that the CTSA and GA model with future inflow are effective methods for searching optimal reservoir rule curves that are suitable for using in the future situations.

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